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Disease and forest production in Western Australia with particular reference to the effects of *Phytophthora cinnamomi*

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Abstract

The native forests of Western Australia are valuable for production of timber and water, and for conservation and recreation. Plant diseases affect all of these values. Timber production is reduced and the aesthetic experience of the forest changed when trees are killed or lose vigour. Conservation values are affected when species are eliminated locally or forest structures are changed. The main forest diseases recognised in Western Australia are caused by fungi. They are dieback caused by *Phytophthora cinnamomi*, straw rots (*Armillaria luteobubalina*) and karri brown wood (associated with a variety of fungi).

The effect of one of these diseases, jarrah dieback, on forest production was examined in a five year dendrometer study of tree growth. Overall diameter increment of jarrah on dieback-affected sites was less than on either control or thinned but dieback-free sites. Growth rates varied greatly both between sites and between trees on the same sites irrespective of disease status. As a consequence, the effects of dieback on tree growth are difficult to separate from site factors (*e.g.* rainfall, soil, topographical position) and tree factors (*e.g.* genetic potential, age, vigour and dominance class).

Introduction

The native forests and woodlands are a major asset of Western Australia. State forests are the source of nearly 2 million cubic metres of timber products annually (Table 1), of approximately half the water used by cities and for irrigation in the south-west (total storage capacity 9 10^5 megalitres, Olsen & Skitmore 1991) and provide a varied environment for tourism, recreation and education. Conservation values of the forests are also high as, even in areas subject to logging, disturbance has been much less intense than in neighbouring agricultural or urban areas (Havel 1989).

Table 1

Timber production in Western Australia in 1992/93 (from Conservation and Land Management 1993).

Category	Volume (m^3)
Eucalyptus marginata (jarrah)	385 819
Eucalyptus calophylla (marri)	45 587
Eucalyptus diversicolor (karri)	195 613
Pinus spp. (mainly *Pinus radiata*)	149 487
Non-sawlog (*e.g.* chiplogs, firewood)	1 100 077

Diseases affect forest values adversely by affecting growth, hydrological cycles, stand structure and species composition. The major disease problem of Western Australia's native forests is dieback associated with the soil-borne fungus *Phytophthora cinnamomi*. The disease is often termed "jarrah dieback" because of its highly visible effects on this dominant forest species. Affected jarrah typically dies after one or more cycles of crown death alternating with periods of partial recovery. Other significant forest diseases identified in Western Australia are root rots and basal cankers caused by the fungus *Armillaria luteobubalina*, and brown wood and rots of karri associated with a number of fungi.

Armillaria luteobubalina occurs throughout the south-west forests (Pearce *et al.* 1986, Shearer 1992, Shearer & Tippett 1988). Although *Armillaria luteobubalina* is capable of infecting a wide range of hosts including jarrah, marri, karri, wandoo and *Banksia grandis*, it seldom causes deaths of more than individual trees or small patches of trees. *Armillaria luteobubalina* lesions are usually contained by periderms if the host is a vigorous mature tree. However, mortalities can occur when lesions cannot be contained or large numbers of infections are initiated. Trees of highly susceptible species (*e.g. Eucalyptus wandoo*) or which are small, whose vigour has been reduced by intense competition or drought, or are close to *A. luteobubalina*-colonised stumps supporting high local inoculum populations, are at the greatest risk of damage.

Brown wood of karri is a discolouration associated with infection by a number of fungi with *Stereum hirsutem* and *Hymenochaete* sp. being the most common (Davison & Tay 1991). Brown wood does not affect timber strength (Siemon, CALM, Perth, *pers. comm.*) but it is unsightly and has been identified as a precursor to rots (Davison & Tay 1991). Such rots are unlikely to develop in timber which has been dried to less than 20% moisture content (Bootle 1983). The extent of the brown wood problem in karri is difficult to assess as the discolouration is visible only when stems are sectioned.

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However, a limited study of regrowth karri mainly from the Treen Brook area found brown wood in 73% of 270 trees sampled (Davison & Tay 1991). The generality of this finding is untested.

The effects of *A. luteobubalina* and karri brown wood on forest values and forest production are less well understood than are the effects of *P. cinnamomi*. More extensive reviews of current knowledge of the occurrence and biology of *P. cinnamomi, A. luteobubalina*, brown wood and other fungal pathogens and saprophytes of the south west forests are given by Hilton *et al.* (1989) and Shearer (1992).

This paper will illustrate some of the difficulties of assessing the effect of pathogens on forest production by describing recent attempts to measure the effect of *P. cinnamomi* dieback on growth of jarrah.

Jarrah dieback

Phytophthora cinnamomi infestation of native forest causes changes in stand density and species composition (Davison & Shearer 1989) which affect non-timber values such as water yield (Schofield 1990), biodiversity, honey production and recreation. *Pinus radiata* on susceptible sites can also be killed or damaged (Chevis & Stukely 1982, Butcher *et al.* 1983).

Phytophthora cinnamomi dieback affects an estimated 14.2% of the jarrah forest (32 000 ha of the 225 000 ha of jarrah forest mapped by aerial photography; H Campbell, cited by Davison & Shearer 1989). The northern and western parts of the jarrah forest are affected more than the southern areas (Batini & Hopkins 1972) possibly because of differences in climate and soils which affect fungal behaviour and in the intensity of human activities which spread the fungus (Shearer 1992).

Initial prognoses for the survival of the jarrah forest were pessimistic because of early experiences of rapid death of virtually all jarrah trees over large areas. Accordingly, much early work was directed to replacing the native jarrah with *Phytophthora* resistant exotic species (Bartle & Shea 1978). Better understanding of the factors affecting the spread of *P. cinnamomi* in the forest and of jarrah's ability to resist *P. cinnamomi* (see Shearer & Tippett 1989) coupled with changing community attitudes to forest management has resulted in a more optimistic outlook. Management policy now emphasises maintaining as much of the jarrah forest as possible and limiting the spread of *P. cinnamomi* to uninfected forest by controlling access (Conservation and Land Management 1987, 1989).

Quantifying the effect of dieback on forest production has been difficult. Estimates of the loss of diameter increment of jarrah due to dieback vary from an 87% reduction (Podger 1972), through a smaller 12% loss (Crombie & Tippett 1990) to no effect or even a slight increase (Davison & Tay 1988). It is probable that the outcome depends on the balance between the level of damage caused by the pathogen and the benefits of reduced competition as susceptible neighbouring trees and understorey plants are killed.

Methods

Nine sites comprising a dieback-affected and an adjacent dieback-free area were chosen in the jarrah forest between Perth and Dwellingup. The association of *P. cinnamomi* with the observed dieback symptoms was confirmed by recovery of *Phytophthora* from the dieback-affected areas at all sites. A further five dieback-free sites were included to extend the range of site occupation on dieback free sites to encompass that of the dieback sites. Sites selected included elements of the S site type of Havel (1975) as this is representative of the main area available for logging in the northern part of the jarrah forest. The dieback-affected sites and their characteristics are listed in Table 2. Four sites (Angle Swamp, Boundary Road, Canning Dam Road and Karragullen) were those for which initial results have been discussed by Crombie & Tippett (1990).

A low intensity fire affected the dieback-affected part only of the Ashendon Road site in the autumn of 1990. Such fires have been associated with increased growth rates (Davison & Tay 1988, Kimber 1978) but the effect in this instance in unknown.

Dominant or co-dominant trees of as nearly similar diameter as could be managed were selected on each of the dieback-affected and dieback-free plots. Selected trees were fitted with stainless steel dendrometer bands (Liming 1957) and increments recorded monthly.

Results

Mortality

Growth of jarrah on dieback sites was monitored for three to five years giving a total of 548 tree-years (number of trees x number of years). Eight trees on three sites died during this time (1.5 % per annum). This compares with previous re-

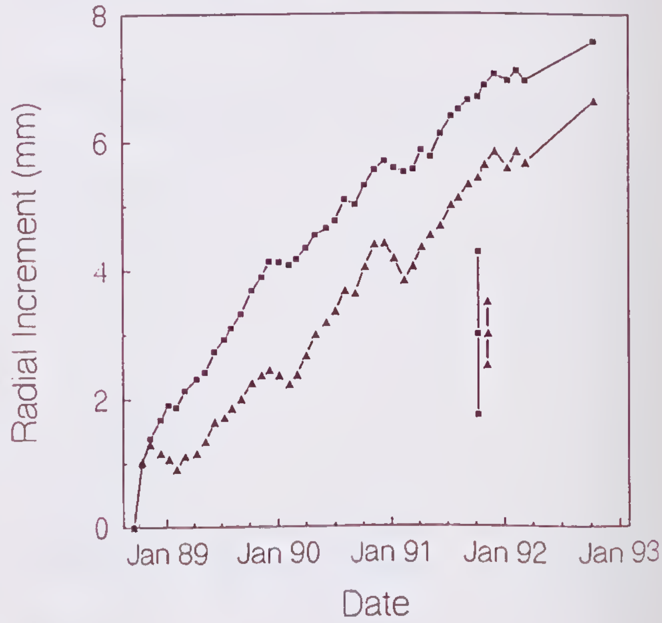

Figure 1. Radial increment of trees on adjacent dieback-free and dieback-affected areas at Pumping Station Road. Standard errors of increments between September 1988 and October 1991 are included (vertical bars) to show variability. There were 11 trees on the dieback-free area (■) and 23 in the dieback-affected area (▲).

Table 2
Characterisations of stands: C = Control, D=Dieback-affected, T=Thinned. Soil type; L=lateritic boulders and lateritic gravel, S-L=sandy soil with occasional lateritic rocks, S=sandy soil without lateritic boulders.

	Soil Type	Rainfall (mm)	Number of Trees		Diameter under bark (mm)		Height (m)		Stand Density (Stems ha^{-1})		Basal Area (m^2 ha^{-1})	
Dieback Sites			C	D	C	D	C	D	C	D	C	D
Angle Swamp	L	850	10	10	247	275	14	14	789	280	27	21
Ashendon Road	L	1050	12	12	330	323	18	18	1 353	1 626	31	29
Boundary Road	S-L	1050	11	11	226	251	18	19	865	654	28	22
Canning Dam Road	L	1250	10	11	282	265	19	19	1 054	318	31	24
Hay Creek	S	1100	11	11	326	306	17	15	926	912	34	32
Gravel Pit	S	1250	11	11	376	355	19	20	1 050	556	38	30
Karragullen	L	1250	10	7	252	255	16	16	1 455	919	31	24
Pumping Station Road	S	1200	12	21	303	248	18	15	934	458	34	20
Sawyers Valley	S-L	900	12	11	261	265	17	14	690	269	22	16
Thinned Sites			C	T	C	T	C	T	C	T	C	T
Banksiadale Road	L	1300	20	19	337	349	23	25	988	638	35	15
Jarrahdale Road	S-L	1200	12		314		24		1 549		44	
Mundaring	S-L	1100	40	60	251	246	17	17	1 498	1 472	29	21
Roma Road	L	1250	20	20	295	301	23	22	1 722	296	30	13
Torrens Road	L	1300	20	20	282	287	21	20	1 348	914	36	10

ports of report of 4.2 % per annum deaths (three sites, Podger 1972) and 0.84 % deaths per annum (two sites, Davison & Tay 1988). No trees died on dieback-free sites during this study. Deaths were unevenly distributed between seasons and also between years. Five deaths occurred when evaporative demand was high in mid to late summer (February to April) and three when it was rising in spring (September or October). More deaths occurred in 1991 and 1992 than in 1988, 1989 or 1990.

Growth

Radial increment varied between dieback-affected and dieback-free sites and also between trees within sites, between sites and from month to month and year to year. Typical growth patterns are illustrated with data from the Pumping Station Road site in Figure 1.

Stem growth occurred when soil water was readily available (from the beginning of rains in April or May until January or February) but was slowed by low temperatures during winter (June to August; see also Abbott & Loneragan 1983). Slower diameter growth or slight shrinkage were associated with water deficits during summer drought (February to March).

Growth patterns of trees on dieback-affected areas were similar to those of trees on dieback-free sites with the exception that summer shrinkage began one to two months earlier and was more pronounced in trees on dieback-affected sites. The effect of dieback on growth was examined by analysis of covariance using the total radial increment occurring between October 1988 and October 1991 (Table 3). Data were transformed to square roots to reduce heteroscedascity. Stand basal area (SBA) and site were identified as the major covariates by step-wise regression.

Table 3
Analysis of covariance. Tests were conducted by applying the SAS procedure General Linear Models to square root transformed radial increments from October 1988 to October 1991. SBA= Stand Basal Area.

Source	DF	Sum of Squares	Mean Square	F Value	P
SBA	1	13.83	13.83	21.12	0.002
Site	13	26.88	2.07	3.16	0.05
Dieback	1	1.93	1.93	2.94	0.12
Site* Dieback	8	5.24	0.65	1.93	0.05
Within plot	411	139.52	0.34		
Total	434	201.13			

Phytophthora cinnamomi dieback was less a predictor of tree growth ($p = 0.12$) than either stand basal area ($p = 0.002$) or site ($p = 0.05$). The low level of significance in the results reflects the small sample sizes used (10 to 12 trees per site). A *post hoc* consideration of the variances in growth suggests that a sample size of 30 trees would have been needed to obtain differences between growth of trees on dieback-affected and dieback-free sites significant at the 5% level.

Comparison of the adjusted mean squares solutions to the model (Table 4) shows that increment on dieback sites averaged about 80% that on dieback-free sites. However, growth of trees on the dieback-affected areas relative to dieback-free areas varied widely from a minimum of 38% on the Angle Swamp site to a maximum of 140% at Ashendon Road.

Table 4

Mean of measured radial increments and least squares adjusted mean increments (as square root of increment) on dieback-free control (C) or dieback-affected (D) sites. Covariates used in the adjustment were stand basal area and site.

Site	Radial Increment (√mm) Measured		Least squares estimate		Ratio (D/C)
	C	D	C	D	
Angle Swamp	2.1	1.4	2.1	1.3	0.62
Ashendon Road	1.6	1.8	1.6	1.9	1.16
Boundary Road	1.9	2.1	2.0	1.9	0.97
Canning Dam Road	2.6	2.4	2.7	2.2	0.83
Hay Creek	2.2	1.7	2.3	1.8	0.78
Gravel Pit	2.1	2.3	2.3	2.3	1.01
Karragullen	2.7	2.9	2.7	2.7	1.02
Pumping Station Road	2.4	2.1	2.4	2.0	0.83
Sawyers Valley	1.8	2.1	1.8	1.8	1.03

Growth of trees on dieback sites was not affected in a consistent way by outcroppings of lateritic ironstone or sandy soils which might indicate differences in drainage. Thus while growth at two sites with masses of exposed lateritic duricrust (Angle Swamp and Canning Dam Road) was reduced below those of controls, growth was about the same at another site (Karragullen) and was increased substantially at a fourth (Ashendon Road). Of the sites with sandy soils, growth was reduced on the dieback areas at two sites (Pumping Station Road and Hay Creek) but was virtually unaffected on another two sites (Boundary Road and Gravel Pit).

Discussion

Synchronisation of tree deaths with times of high or rising evaporative demand and higher death rates in years with unusually high rainfall has been noted before (Davison 1988, Fagg *et al.* 1986, Shea *et al.* 1983, Hamilton, 1951 *unpub. report* cited by Dell & Malajzuk 1989, Tippett *et al.* 1985). Both observations are consistent with the expected behaviour of *P. cinnamomi* which requires water for dissemination and infection and which damages the roots necessary for uptake of water during summer drought (Crombie & Tippett 1990).

Overall radial increment of trees on dieback-affected sites was about 80% that of similar trees on nearby dieback-free sites, although the estimates are imprecise (see above). The lack of precision is disappointing given that the biotic and environmental factors affecting *P. cinnamomi* are well known (*e.g.* Shearer & Tippett 1989).

The greatest difficulty encountered was the great variability in tree vigour, age, size, spacing, genotype, topography and soil type which occur in native forests (Stoneman *et al.* 1989). Determination of the effects of disease on growth of jarrah are made more difficult by the very slow growth of jarrah in native forest (diameter increments of 2-3 mm yr^{-1}) which require long periods before the effects of disease on growth become evident.

Locating suitable control plots was also a problem. Potential control sites adjacent to diseased areas are often disease-free because they have some characteristic which has prevented the pathogen occupying the site. Differences in soil type, amount of deep drainage and sub-surface topography may be very important in determining disease occurrence but are difficult to identify in the field.

Even when the factors controlling disease occurrence are known, other factors limit site selection. In particular, the location, shape and size of dieback outbreaks is largely dependent on the interaction of site hydrologic characteristics and forest operations. Dieback infestations originating from soil dropped from vehicles (Podger 1972) usually spread downhill along drainage lines leaving the tracks from which the infections began as the boundary between dieback-affected and dieback-free areas. Such tracks are often used as convenient boundaries for logging coupes or as firebreaks (as happened at the Ashendon Road site) so that stand structure and history are often not the same on both sides of the track. Areas downstream and possibly to the side of known infections must also be considered to be either infected or highly likely to become so as spores are distributed by mass flows of soil water (Kinal *et al.* 1993). Finally, plot access tracks have to be suitable for wet weather use without risking establishing new *P. cinnamomi* infestations.

The time since infection, occurrence of subsequent reinfections and the rate and extent at which dieback develops may also be important to the effect of dieback on growth but are seldom known when studying disease in native forests. Similarly, genotypic (Butcher *et al.* 1984) and environmental factors, including temperature and summer drought (Shearer & Tippett 1989, Tippett *et al.* 1987), are likely to affect the rate of development and severity of disease expression but cannot be controlled in most field situations.

Conclusion

This study has recorded both reductions and increases in growth of jarrah on *P. cinnamomi* infested sites. The provisional conclusion is that average diameter increments of trees on dieback sites are approximately 80% those on dieback-free sites when adjusted for differences in site quality and competition. Differences in the effect of *P. cinnamomi* on growth of particular jarrah trees are likely to be related to tree, site and climatic differences.

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